Structural heterogeneity in the megathrust zone and mechanism of the 2011 Tohoku-oki earthquake (Mw 9.0)

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[1] The great 2011 Tohoku-oki earthquake (Mw 9.0) and its 339 foreshocks and 5,609 aftershocks (9–27 March 2011) were relocated using a three-dimensional seismic velocity model and local P and S wave arrival times. The distribution of relocated hypocenters was compared with a tomographic image of the Northeast Japan forearc. The comparison indicates that the rupture nucleation of the largest events in the Tohoku-oki sequence, including the mainshock, was controlled by structural heterogeneities in the megathrust zone. **Citation:** Zhao, D., Z. Huang, N. Umino, A. Hasegawa, and H. Kanamori (2011), Structural heterogeneity in the megathrust zone and mechanism of the 2011 Tohoku-oki earthquake (Mw 9.0), *Geophys. Res. Lett.*, *38*, L17308, doi:10.1029/2011GL048408.

1. Introduction

[2] The great Tohoku-oki earthquake (Mw 9.0) occurred at 14:46 local time (05:46 UTC) on 11 March 2011 in the forearc region of the Northeast (NE) Japan subduction zone (Figure 1). It was caused by subduction of the Pacific plate beneath the Okhotsk plate. A large foreshock of this earthquake took place at 11:45 local time on 9 March 2011, with a magnitude (M_{JMA}) of 7.3, as determined by the Japan Meteorological Agency (http://www.jma.go.jp). Following the Tohoku-oki mainshock and on the same day, three aftershocks occurred with $M_{JMA} \geq 7.4$, and many smaller aftershocks were recorded and located by the dense seismic network installed on the Japan Islands (Figure 1). Soon after the occurrence of these earthquakes, JMA, United States Geological Survey (USGS) (http://earthquake.usgs.gov) and several other research agencies published hypocentral parameters for these earthquakes. The locations were similar, but significant differences were apparent. For example, with respect to the Tohoku-oki mainshock, the JMA location is: (38.103N, 142.861E, 24.0 km), whereas the USGS location is: (38.322N, 142.369E, 32.0 km). The difference between them is over 50 km and was caused by several factors, such as the differences in the arrival-time data sets and the velocity models used for the earthquake location. The JMA hypocenters are determined using the seismic stations on the Japan Islands and the JMA one-dimensional (1-D) velocity model [*Ueno et al.*, 2002], whereas the USGS hypocenters are determined with the globally distributed seismic stations and a global 1-D velocity model [*Kennett and Engdahl*, 1991].

[3] Precise hypocenters are of fundamental importance in many disciplines of seismology, being necessary to estimate the rupture process on the fault plane, strong ground motions and crustal and upper-mantle structure in the source area, and so on. The hypocentral distribution of earthquakes in the NE Japan forearc under the Pacific Ocean has been investigated by deploying ocean-bottom-seismometer (OBS) stations [*Hino et al.*, 2000; *Miura et al.*, 2003], and using sP depth phases detected on the seismograms from the dense seismic network on the Japan Islands (Figure 1) [e.g., *Umino et al.*, 1995; *Mishra et al.*, 2003; *Wang and Zhao*, 2005; *Gamage et al.*, 2009; *Zhao et al.*, 2009]. In this work we used a three-dimensional (3-D) seismic velocity model [*Huang et al.*, 2011] to relocate the great Tohoku-oki earthquake and its 339 foreshocks and 5,609 aftershocks. Then the distribution of the relocated hypocenters is compared with the tomographic image in the NE Japan forearc, which shed light on the generating mechanism of the 2011 Tohoku-oki earthquake sequence.

2. Earthquake Relocation

[4] Several permanent short-period seismic networks have been deployed on the Japan Islands, including the JMA Seismic Network, the Japan University Seismic Network, and the High-Sensitivity Seismic Network [*Okada et al.*, 2004]. These seismic networks have been combined in order to constitute a nationwide, high-quality network, known as the *Kiban network* that includes over 1,800 seismic stations densely and uniformly covering the Japan Islands [*Okada et al.*, 2004; *Hasegawa et al.*, 2009]. Since October 1997 waveform data recorded by the Kiban network have been transmitted to and processed by JMA to monitor the seismic activity in and around Japan [*Okada et al.*, 2004]. P and S wave arrival times are measured from the three-component seismograms with an automatic processing system and monitored by the network staff daily. The accuracy of the arrival times is estimated to be 0.05–0.15 s for P-waves and 0.1–0.2 s for S-waves. The arrival-time data are used with the JMA 1-D velocity model [*Ueno et al.*, 2002] to determine the hypocentral parameters for each earthquake. The resulting data base containing the P and S wave arrival times and the hypocentral parameters is known as the *JMA Unified Catalogue* [*Okada et al.*, 2004].

[5] We used the Kiban network stations in NE Japan (Figure 1) to relocate the Tohoku-oki earthquake sequence. Note that six OBS stations located in the Pacific Ocean were used, which provided valuable constraints on the locations of the suboceanic events, particularly for those events that

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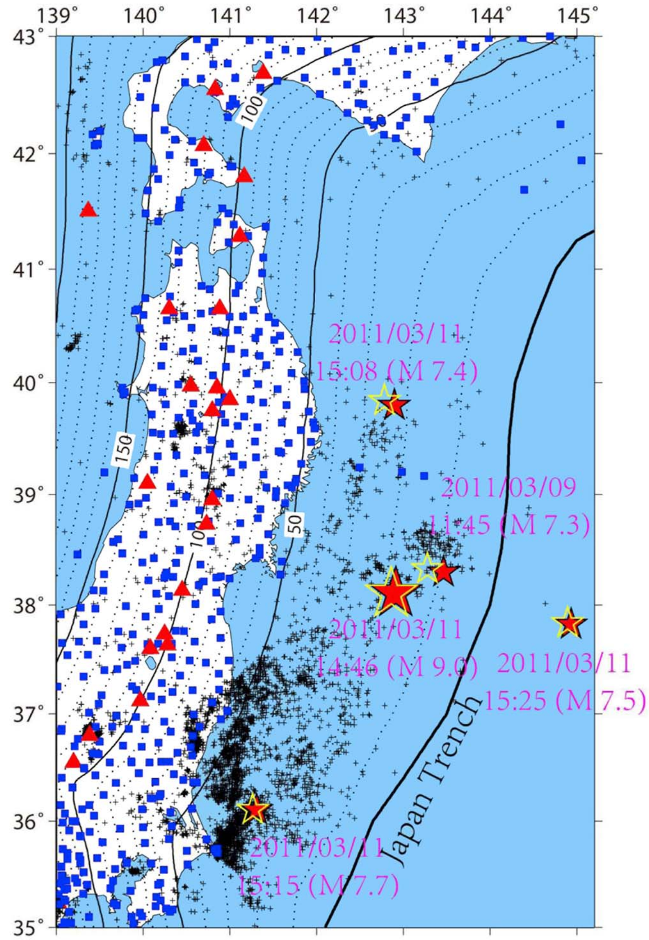

Figure 1. Map showing the relocated epicentral locations (red stars) of the great 2011 Tohoku-oki earthquake (Mw 9.0) on 11 March 2011 and its largest foreshock (M_{JMA} 7.3) on 9 March 2011 and major aftershocks (M_{JMA} > 7.0) on 11 March 2011. The open yellow stars show the epicenters determined by the Kiban seismic network (JMA Unified Catalogue). The blue squares show the Kiban network stations used to relocate the earthquakes. The red triangles show the active arc volcanoes. The solid and dotted contour lines show the depths to the upper boundary of the subducting Pacific slab. The thick solid line denotes the Japan Trench. The cross symbols show the relocated epicenters of the seismicity during 9–27 March 2011.

occurred close to the OBS stations. We relocated 5,949 events of the 2011 Tohoku-oki earthquake sequence from 9 March 2011, when the M_{JMA} 7.3 foreshock occurred, to 27 March 2011 using the high-quality P and S wave arrival-time data from the JMA Unified Catalogue. The arrival-time data for the events after 27 March 2011 were not available, at the time the present work was being undertaken.

[6] In this work the hypocentral parameters were determined for each earthquake by inverting the P and S wave arrival-time data iteratively using a least-squares method [*Zhao et al.*, 1992, 2009]. A 3-D ray-tracing technique [*Zhao et al.*, 1992] was used to calculate accurate travel times and ray paths in the 3-D velocity model [*Huang et al.*, 2011]. The changes in the hypocenters before and after relocation are smaller (<5 km) for the events beneath land, whereas the changes become larger for events under the Pacific Ocean, being 5–30 km, in particular, for events near the Japan Trench. After relocation most suboceanic events move toward the east, as compared with their JMA locations. The relocated hypocenters of the 5 biggest events ($M_{JMA} \geq 7.3$; Table 1) are all located at or very close to the upper boundary of the subducting Pacific slab (Figures 2b–2e), which is consistent with their thrust focal mechanism (JMA, http://www.jma.go.jp) [*Lay et al.*, 2011; *Koper et al.*, 2011]. For the 5 biggest events, we examined their seismograms recorded by the High-Sensitivity Seismic Network and searched for sP depth phases, but did not succeed because the seismograms are very complicated, possibly due to the complex rupture processes.

3. Tomography and Seismogenesis in the Megathrust Zone

[7] The 3-D velocity model [*Huang et al.*, 2011] was determined by inverting 310,749 P and 150,563 S wave arrival times from 4,655 local earthquakes that occurred in the crust and the subducting Pacific slab from the Japan Trench to the Japan Sea. *Huang et al.* [2011] relocated the suboceanic events precisely using P and S arrival times as well as sP depth-phase data that were measured from the seismograms recorded by the seismic stations on the NE Japan land area, similar to the previous studies [*Umino et al.*, 1995; *Mishra et al.*, 2003; *Wang and Zhao*, 2005; *Gamage et al.*, 2009; *Zhao et al.*, 2009]. The 3-D velocity structure under the Pacific Ocean and the Japan Sea was determined reliably with a resolution of 30–40 km [*Huang et al.*, 2011]. As compared with the previous tomographic studies [e.g., *Zhao et al.*, 2009], *Huang et al.* [2011] used many more suboceanic events that were relocated with sP depth phase and the events are distributed more densely and uniformly in the forearc, so they could determine the 3-D velocity structure under the Pacific Ocean more reliably.

[8] Significant velocity variations are noticeable in the megathrust zone under the NE Japan forearc (Figure 2a). Three low-velocity (low-V) anomalies exist off Sanriku, off Fukushima and off Ibaraki (Figure 2a). There is a correlation between the velocity variation and the distribution of large earthquakes ($M_{JMA} \geq 6.0$) that occurred from 1900 to 2008, most of which are considered to be interplate thrust-type earthquakes [*Umino et al.*, 1990; *Usami*, 2003; *Yamanaka and Kikuchi*, 2004; *Zhao et al.*, 2009]. These large earthquakes were located using the seismic network on the Japan Islands and their epicentral locations are accurate to 10 km [*Umino et al.*, 1990; *Usami*, 2003; *Yamanaka and Kikuchi*, 2004]. Most of the large earthquakes are located in the high-velocity (high-V) patches or at the boundary between the low-V and high-V zones, with only a few situated in the low-V patches (Figure 2a).

[9] The 2011 Tohoku-oki mainshock and its foreshock (M_{JMA} 7.3) on 9 March 2011 are located in a significant high-V zone off Miyagi (Figure 2a). The northern aftershock (M_{JMA} 7.4) that occurred at 15:08, 11 March 2011 is located at the boundary between the off-Sanriku low-V zone and a high-V zone in the north. The southern aftershock (M_{JMA} 7.7) that took place at 15:15, 11 March 2011 is located at the northern edge of the off-Ibaraki low-V zone. Such a pattern of the hypocenter distribution for the 2011 Tohoku-oki earthquakes is quite consistent with that of the

Table 1. Relocated Hypocentral Parameters of the Great 2011 Tohoku-oki Earthquake (Mw 9.0) and Its Major Foreshock and Aftershocks ($M_{JMA} \geq 7.3$)[a]

Date	Origin-Time (s)	Latitude	Longitude	Depth (km)	M_{JMA}
2011-3-09	11:45 11.54 (0.31)	38.300 (0.013) N	143.464 (0.049) E	7.71 (3.91)	7.3
2011-3-11	14:46 18.14 (0.18)	38.107 (0.009) N	142.916 (0.013) E	14.50 (1.21)	9.0
2011-3-11	15:08 53.05 (0.39)	39.798 (0.012) N	142.896 (0.028) E	22.94 (1.80)	7.4
2011-3-11	15:15 35.34 (0.43)	36.102 (0.014) N	141.319 (0.035) E	32.04 (7.70)	7.7
2011-3-11	15:25 43.15 (3.67)	37.821 (0.030) N	144.935 (0.041) E	14.51 (58.62)	7.5

[a]The values in the brackets denote the standard errors of the corresponding hypocentral parameters.

large earthquakes from 1900 to 2008 (Figure 2a). The aftershock (M_{JMA} 7.5) that took place at 15:25, 11 March 2011 is located east of the Japan Trench and is considered to be an outer-rise earthquake (JMA, http://www.jma.go.jp) [*Lay et al.*, 2011; *Kanamori*, 1971] beyond the range of the 3-D velocity model.

[10] The 3-D S-wave velocity model [*Huang et al.*, 2011] has a lower resolution in the offshore region, but it shows

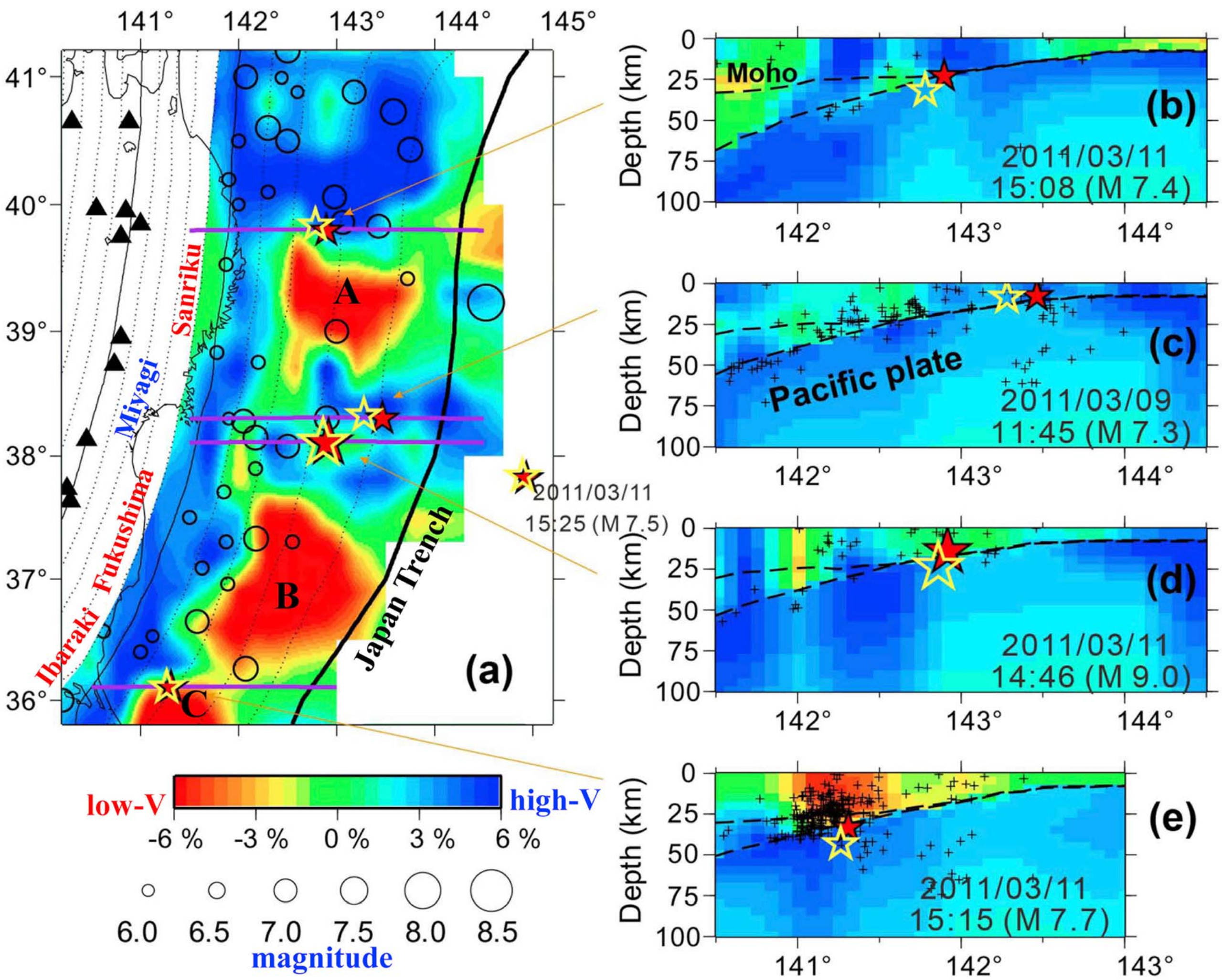

Figure 2. (a) The same as Figure 1 but the color shows P-wave tomographic image in the megathrust zone directly above the upper boundary of the subducting Pacific slab. Red and blue show low and high velocities, respectively. The velocity perturbation (in %) scale is shown at the bottom. Three low-velocity anomalies exist (A) off Sanriku, (B) off Fukushima, and (C) off Ibaraki. The open circles denote the large earthquakes ($M_{JMA} \geq 6.0$) from 1900 to 2008, most of which were interplate earthquakes (see text for details). East-west vertical cross sections of P-wave tomography passing through the epicenters of the 2011 Tohoku-oki (d) mainshock, (c) foreshock, and (b, e) two aftershocks. The color scale is the same as in Figure 2a. The two dashed lines in each cross section represent the Moho discontinuity and the upper boundary of the subducting Pacific plate. The magnitude and origin time of the large earthquakes ($M_{JMA} > 7.0$) are shown in each of the cross sections. Cross symbols denote the relocated earthquakes during 9–27 March 2011 within a 10-km width to each profile.

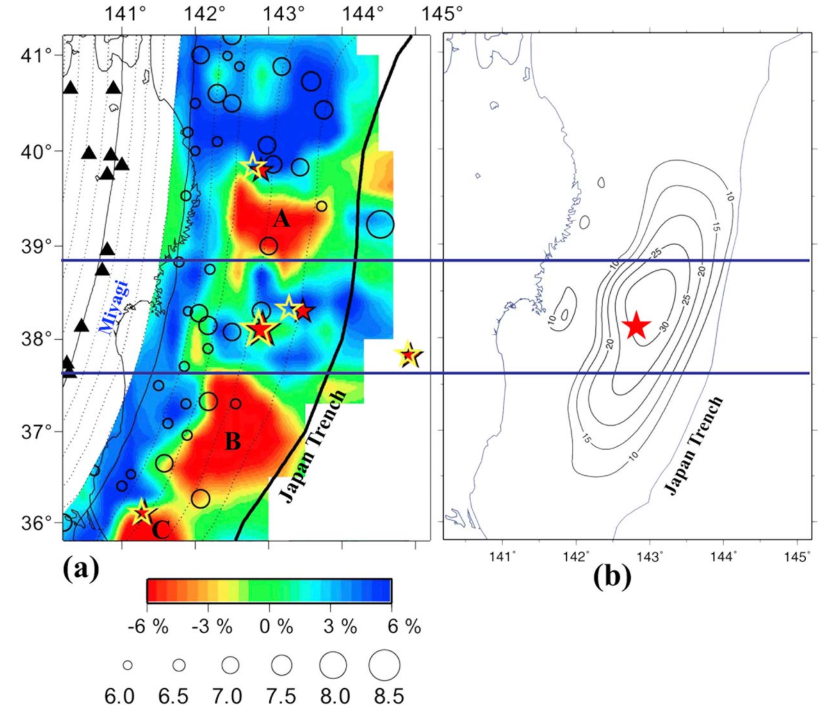

Figure 3. Comparison of (a) P-wave tomography in the megathrust zone (the same as Figure 2a) with (b) the coseismic slip distribution of the 2011 Tohoku-oki earthquake (Mw 9.0, red star) estimated from GPS observations (contour lines with an interval of 5 m) [*Iinuma et al.*, 2011]. The two blue lines show the north-south range of the off-Miyagi high-velocity zone in Figure 3a, where large coseismic slips (>25 m) took place (Figure 3b).

the same pattern as the P-wave velocity model (Figure 2a). In general, the low-V zones exhibit higher Poisson's ratio, whereas the high-V zones show lower Poisson's ratio [*Zhao et al.*, 2009; *Huang et al.*, 2011].

4. Discussion and Conclusions

[11] We suggest that the low-V patches in the megathrust zone (Figure 2a) may contain subducted sediments and fluids associated with slab dehydration [*Mishra et al.*, 2003; *Hyndman and Peacock*, 2003; *van Keken*, 2003; *Huang et al.*, 2011]. Thus the subducting Pacific plate and the overriding continental plate may become weakly coupled or even decoupled in the low-V areas. Large-amplitude reflected waves from the slab boundary were detected in a low-seismicity area under the forearc region off Sanriku [*Fujie et al.*, 2002], as were some slow and ultra-slow thrust earthquakes [*Heki et al.*, 1997; *Kawasaki et al.*, 2001]. Both the seismic reflectors and slow thrust earthquakes are thought to be caused by fluids at the slab boundary [*Fujie et al.*, 2002; *Kawasaki et al.*, 2001], and they are all located in the off-Sanriku low-V zone (Figure 2a).

[12] In contrast, the high-V patches in the megathrust zone (Figure 2a) may result from subducted oceanic ridges, seamounts other topographic highs, or compositional changes on the seafloor of the Pacific plate that become asperities where the subducting Pacific plate and the overriding continental plate are strongly coupled [*Kanamori*, 1986; *Yamanaka and Kikuchi*, 2004]. Thus tectonic stress tends to accumulate in these high-V areas for a relatively long time during subduction, leading to the nucleation of large and great earthquakes in those areas (Figure 2a). The off-Miyagi high-V zone where the Tohoku-oki mainshock and its largest foreshock occurred (Figure 2a) corresponds to the area with large coseismic slip (>25 m) during the Tohoku-oki mainshock [*Lay et al.*, 2011; *Iinuma et al.*, 2011] (Figure 3). This indicates that the off-Miyagi high-V zone is a large asperity (or a cluster of asperities) in the megathrust zone that ruptured during the 2011 Tohoku-oki mainshock.

[13] The distribution of structural heterogeneities in the megathrust zone and its correlation with the distribution of large thrust earthquakes (Figure 2a) suggest varying degrees of interplate seismic coupling from north to south in the NE Japan forearc, possibly controlling the nucleation of the large interplate earthquakes. The great 2011 Tohoku-oki earthquake sequence may be related to such a process. Differences in interplate seismic coupling could result from variations in the frictional behavior of materials [*Pacheco et al.*, 1993; *Heki et al.*, 1997; *Kato and Hirasawa*, 1997; *Miura et al.*, 2003]. The velocity variations in the tomographic image of the megathrust zone (Figure 2a) may be a manifestation of such variations in the frictional behavior.

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References

Fujie, G., J. Kasahara, R. Hino, and T. Sato (2002), A significant relation between seismic activities and reflection intensities in the Japan Trench region, *Geophys. Res. Lett.*, *29*(7), 1100, doi:10.1029/2001GL013764.

Gamage, S., N. Umino, A. Hasegawa, and S. Kirby (2009), Offshore double-planed shallow seismic zone in the NE Japan forearc region revealed by sP depth phases recorded by regional networks, *Geophys. J. Int.*, *178*, 195–214, doi:10.1111/j.1365-246X.2009.04048.x.

Hasegawa, A., J. Nakajima, N. Uchida, T. Okada, D. Zhao, T. Matsuzawa, and N. Umino (2009), Plate subduction, and generation of earthquakes and magmas in Japan as inferred from seismic observation: An overview, *Gondwana Res.*, *16*, 370–400, doi:10.1016/j.gr.2009.03.007.

Heki, K., S. Miyazaki, and H. Tsuji (1997), Silent fault slip following an interplate thrust earthquake at the Japan Trench, *Nature*, *386*, 595–598, doi:10.1038/386595a0.

Hino, R., S. Ito, and H. Shiobara (2000), Aftershock distribution of the 1994 Sanriku-oki earthquake (Mw 7.7) revealed by ocean bottom seismographic observation, *J. Geophys. Res.*, *105*, 21,697–21,710, doi:10.1029/2000JB900174.

Huang, Z., D. Zhao, and L. Wang (2011), Seismic heterogeneity and anisotropy of the Honshu arc from the Japan Trench to the Japan Sea, *Geophys. J. Int.*, *184*, 1428–1444, doi:10.1111/j.1365-246X.2011.04934.x.

Hyndman, R., and S. Peacock (2003), Serpentinization of the forearc mantle, *Earth Planet. Sci. Lett.*, *212*, 417–432, doi:10.1016/S0012-821X(03)00263-2.

Iinuma, T., M. Ohzono, Y. Ohta, and S. Miura (2011), Coseismic slip distribution of the 2011 off the Pacific coast of Tohoku earthquake (M 9.0) estimated based on GPS data—Was the asperity in Miyagi-oki ruptured?, *Earth Planets Space*, in press.

Kanamori, H. (1971), Great earthquakes at island arcs and the lithosphere, *Tectonophysics*, *12*, 187–198, doi:10.1016/0040-1951(71)90003-5.

Kanamori, H. (1986), Rupture process of subduction-zone earthquakes, *Annu. Rev. Earth Planet. Sci.*, *14*, 293–322, doi:10.1146/annurev.ea.14.050186.001453.

Kato, N., and T. Hirasawa (1997), A numerical study on seismic coupling along subduction zones using a laboratory-derived friction law, *Phys. Earth Planet. Inter.*, *102*, 51–68, doi:10.1016/S0031-9201(96)03264-5.

Kawasaki, I., Y. Asai, and Y. Tamura (2001), Space-time distribution of interplate moment release including slow earthquakes and the seismo-geodetic coupling in the Sanriku-oki region along the Japan Trench, *Tectonophysics*, *330*, 267–283, doi:10.1016/S0040-1951(00)00245-6.

Kennett, B., and E. Engdahl (1991), Travel times for global earthquake location and phase identification, *Geophys. J. Int.*, *105*, 429–465, doi:10.1111/j.1365-246X.1991.tb06724.x.

Koper, K., A. Hutko, T. Lay, C. Ammon, and H. Kanamori (2011), Frequency-dependent rupture process of the 11 March 2011 Mw 9.0 Tohoku earthquake: Comparison of short-period P wave backprojection images and broadband seismic rupture models, *Earth Planets Space*, in press.

Lay, T., C. Ammon, H. Kanamori, L. Xue, and M. Kim (2011), Possible large near-trench slip during the great 2011 Tohoku (Mw 9.0) earthquake, *Earth Planets Space*, in press.

Mishra, O. P., D. Zhao, N. Umino, and A. Hasegawa (2003), Tomography of northeast Japan forearc and its implications for interplate seismic coupling, *Geophys. Res. Lett.*, *30*(16), 1850, doi:10.1029/2003GL017736.

Miura, S., S. Kodaira, A. Nakanishi, and T. Tsuru (2003), Structural characteristics controlling the seismicity of southern Japan Trench fore-arc region, revealed by ocean bottom seismographic data, *Tectonophysics*, *363*, 79–102, doi:10.1016/S0040-1951(02)00655-8.

Okada, Y., K. Kasahara, S. Hori, and K. Obara (2004), Recent progress of seismic observation networks in Japan—Hi-net, F-net, K-NET and KiK-net, *Earth Planets Space*, *56*, 15–28.

Pacheco, J., L. Sykes, and C. Scholz (1993), Nature of seismic coupling along simple plate boundaries of the subduction type, *J. Geophys. Res.*, *98*, 14,133–14,159, doi:10.1029/93JB00349.

Ueno, H., S. Hatakeyama, T. Aketagawa, J. Funasaki, and N. Hamada (2002), Improvement of hypocenter determination procedures in the Japan Meteorological Agency, *Q. J. Seismol.*, *65*, 123–134.

Umino, N., A. Hasegawa, and A. Takagi (1990), The relationship between seismicity patterns and fracture zones beneath northeastern Japan, *Sci. Rep. Tohoku Univ. Ser. 5*, *33*, 149–162.

Umino, N., A. Hasegawa, and T. Matsuzawa (1995), sP depth phase at small epicentral distances and estimated subducting plate boundary, *Geophys. J. Int.*, *120*, 356–366, doi:10.1111/j.1365-246X.1995.tb01824.x.

Usami, T. (2003), *Materials for Comprehensive List of Destructive Earthquakes in Japan*, Univ. Tokyo Press, Tokyo.

van Keken, P. (2003), The structure and dynamics of the mantle wedge, *Earth Planet. Sci. Lett.*, *215*, 323–338, doi:10.1016/S0012-821X(03)00460-6.

Wang, Z., and D. Zhao (2005), Seismic imaging of the entire arc of Tohoku and Hokkaido in Japan using P-wave, S-wave and sP depth-phase data, *Phys. Earth Planet. Inter.*, *152*, 144–162, doi:10.1016/j.pepi.2005.06.010.

Wessel, P., and W. Smith (1998), New, improved version of the Generic Mapping Tools released, *Eos Trans. AGU*, *79*(47), 579, doi:10.1029/98EO00426.

Yamanaka, Y., and M. Kikuchi (2004), Asperity map along the subduction zone in northeastern Japan inferred from regional seismic data, *J. Geophys. Res.*, *109*, B07307, doi:10.1029/2003JB002683.

Zhao, D., A. Hasegawa, and S. Horiuchi (1992), Tomographic imaging of P and S wave velocity structure beneath northeastern Japan, *J. Geophys. Res.*, *97*, 19,909–19,928, doi:10.1029/92JB00603.

Zhao, D., Z. Wang, N. Umino, and A. Hasegawa (2009), Mapping the mantle wedge and interplate thrust zone of the northeast Japan arc, *Tectonophysics*, *467*, 89–106, doi:10.1016/j.tecto.2008.12.017.

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